LCA Case Studies

# Assessing Future Energy and Transport Systems: The Case of Fuel Cells

## Part I: Methodological Aspects

**Part 1: Methodological Aspects [Int J LCA 8 (5) 283 – 289 (2003)] • Part 2: Environmental Performance [Int J LCA 8 (6) 2003]**

**Preamble.** This series of two papers which is based on a PhD thesis (Pehnt 2002a) discusses the assessment of fuel cells as future energy and transport systems from two perspectives. Part 1 presents methodological issues associated with the future character of the systems and the need of forecasting process steps and uses the production of an SOFC stack as illustration. Part 2 presents the results of LCAs of fuel cells in stationary and mobile applications based on the methodology discussed before.

**Martin Pehnt**

Institute for Energy and Environmental Research Heidelberg (Ifeu), Wilckensstr. 3, D-69120 Heidelberg, Germany (martin.pehnt@ifeu.de)

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**Abstract**

**Goal, Scope and Background.** Assessing future energy and transport systems is of major importance for providing timely information for decision makers. In the discussion of technology options, fuel cells are often portrayed as attractive options for power plants and automotive applications. However, when analysing these systems, the LCA analyst is confronted with methodological problems, particularly with data gaps and the requirement of an anticipation of future developments. This series of two papers aims at providing a methodological framework for assessing future energy and transport systems (Part 1) and applies this to the two major application areas of fuel cells (Part 2).

**Methods.** To allow the LCA of future energy and transport systems forecasting tools like, amongst others, cost estimation methods and process simulation of systems are investigated with respect to the applicability in LCAs of future systems (Part 1). The manufacturing process of an SOFC stack is used as an illustration for the forecasting procedure. In Part 2, detailed LCAs of fuel cell power plants and power trains are carried out including fuel (hydrogen, methanol, gasoline, diesel and natural gas) and energy converter production. To compare it with competing technologies, internal combustion engines (automotive applications) and reciprocating engines, gas turbines and combined cycle plants (stationary applications) are analysed as well.

**Results and Discussion.** Principally, the investigated forecasting methods are suitable for future energy system assessment. The selection of the best method depends on different factors such as required ressources, quality of the results and flexibility. In particular, the time horizon of the investigation determines which forecasting tool may be applied. Environmentally relevant process steps exhibiting a significant time dependency shall always be investigated using different independent forecasting tools to ensure stability of the results.

The results of the LCA (Part 2) underline that principally, fuel cells offer advantages in the impact categories which are typically dominated by pollutant emissions, such as acidification and eutrophication, whereas for global warming and primary energy demand, the situation depends on a set of parameters such as driving cycle and fuel economy ratio in mobile applications and thermal/total efficiencies in stationary applications. For the latter impact categories, the choice of the primary energy carrier for fuel production (renewable or fossil) dominates the impact reduction. With increasing efficiency and improving emission performance of the conventional systems, the competition regarding all impact categories in both mobile and stationary applications is getting even stronger.

The production of the fuel cell system is of low overall significance in stationary applications, whereas in automotive applications, the production of the fuel cell power train and required materials leads to increased impacts compared to internal combustion engines and thus reduces the achievable environmental impact reduction.

**Recommendations and Perspectives.** The rapid technological and energy economic development will bring further advances for both fuel cells and conventional energy converters. Therefore, LCAs at such an early stage of the market development can only be considered preliminary. It is an essential requirement to accompany the ongoing research and development with iterative LCAs, constantly pointing at environmental hot spots and bottlenecks.

**Keywords:** Fuel cells; solid oxide fuel cell (SOFC); data gaps, forecasting; cost estimation method; energy systems; life cycle assessment (LCA); transport systems

### Introduction

Fuel cells are energy systems with a high potential for environmentally friendly energy conversion. They convert the chemical energy of a fuel and oxygen continuously and electrochemically into electrical energy (for details on the function of fuel cells, see Pehnt M 2002b). The 'secret' of fuel cells is the electrolyte which separates the two reactants, $H_2$ and $O_2$, to avoid an uncontrolled explosive reaction.

Fuel cells can be used in stationary and mobile applications. Depending on the type of fuel cells, stationary systems include small residential, medium sized cogeneration or large power plant applications. In the mobile sector, fuel cells, particularly low-temperature systems, can be used for heavy-duty and passenger vehicles, for trains, boats or auxiliary power units for air planes. Mobile applications also include portable low power systems for various uses (Pehnt M 2002b).

From an environmental point of view, the high efficiency can lead to a significant reduction of fossil fuel use and of

greenhouse gas emissions. In addition, the electrochemical nature of the reaction, the low temperature of the process steps involved and the necessity to remove impurities in the fuel (such as sulfur) result in extremely low local emissions – an important feature especially in highly populated areas. In vehicle applications, particularly at low speed, reductions in noise emissions are to be expected.

Thus, clear environmental advantages can be expected in the various application areas of fuel cells. However, for an environmental evaluation of the different service supply options, an investigation of the complete life-cycle of these options is necessary to ensure that no environmental aspect is neglected.

As such innovative energy systems are typically more efficient and ecologically benign in the use phase, the environmental relevance of the production of the system and the fuel are of increasing importance. This is true in *relative* terms – meaning that the share of these life cycle stages gains in importance – but might also be true in *absolute* terms because more ecologically relevant materials (such as catalyst materials) and fuels might be involved. To ensure that fuel cells offer environmental advantages, an assessment of these systems at an early stage of product development is desirable, even more so as at this time, the variety of material, fuel and system options is much broader.

## 1 Assessing Future Energy Systems

However, methodological problems are associated with the assessment of future energy systems which are at an early stage of product development. The problem, which is common to assessing most product systems of strategic importance, is the discrepancy between the importance of the assessment at an early stage of product development, at which most development options are still available, and the state of knowledge about the product system (Hungerbühler 1999).

This problem is common to many different investigation methods used within the framework of technology assessment (TA) where it has been termed control dilemma (Collingridge 1980). In TA, an anticipative, comprehensive assessment oriented towards decision-making (Paschen and Petermann 1991) is carried out. This 'early warning function' requires prospective analyses; a status-quo or retrospective assessment of the accountancy type (Weidema et al. 1999) is not sufficient. However, the future character of the investigated system leads to inherent methodological problems.

In TA, the 'forecasting dilemma' has led to suggestions of restricting the time horizon of the investigations (Kornwachs 1991) or even to complete rejection of that instrument, especially when applied to investigating innovative technologies (problem induced TA which analyse areas of concern preventively, continously and as an integral aspect of technology development itself (Ropohl 1993)).

Inevitably, the assessment, whether TA or more specifically LCAs, should be interpreted as an investigation *process* with iterative steps, constant up-dating and interaction between the analysts and the developers of the investigated technologies (Grin 1998). However, this process, also termed 'Constructive Technology Assessment (CTA)', is not in all cases realisable. Even then, the deduction of useful conclusions must be possible. The use of forecasting elements should, therefore, also apply forecasting tools developed for instance in management science. The aim is not to achieve a correct forecast, as pointed out by Grunwald. "The anticipation of future as future reality cannot be successful. As support for decision making, TA must therefore focus (...) on hypothetical impacts of singular decisions" (Grunwald and Langenbach 1999).

In particular, LCAs of future energy technologies exhibit a number of concrete methodological problems, such as

- an increased need for **allocation** or system expansion due to increased complexity and enhanced use of joint or combined products which is partly due to higher environmental standards of the systems (e.g. cogeneration in fuel cells or joint production of carbon black and hydrogen in the Kværner CB&H process (see Part 2)). In addition, the determination of suitable 'credit systems' in a system expansion (avoided burden) approach becomes increasingly difficult because of the longterm perspective of the study;
- an increasingly **difficult distinction between foreground systems** (defined as consisting of processes which are under control of the decision-maker for which an LCA is carried out (Frischknecht 1998, Grunwald and Langenbach 1999) and supply the functional unit (Azapagic and Clift 1999)) **and background systems** because of multiple feedback mechanisms (e.g. different power trains prefer different fuels or fuels in different qualities thus strongly influencing the background system of fuel supply);
- an increasing need to **consider the infrastructure** (manufacturing the energy system) because
  - a trend towards decentralisation in electricity production means that the importance of infrastructure may increase because small systems often require higher specific material and energy inputs
  - a trend towards renewable energy systems implies that the fuel supply and the use phase are often of minor importance compared to the production of the energy systems
  - a trend towards cleaner energy systems with lower direct impacts (for instance direct emissions from power plants) also leads to an increased relative importance of manufacturing the system
  - cleaner and more efficient power plants often require more sophisticated components with higher impacts for their production (e.g. catalyst materials in fuel cells)
  - sometimes completely new infrastructures have to be set up (e.g. hydrogen fuelling infrastructure for fuel cell vehicles);
- different kinds of **data gaps** (Lindfors et al. 1994). In the LCI process, the lack of data or of representative data as described in (Huijbregts et al. 2001) is an important source of data uncertainty. Here, we suggest to categorise the data gaps according to the causes for the data deficit (**Table 1**). Data gaps of type 1, i.e. gaps due to confidentiality of data, can be avoided by agreements of confidentiality and aggregation of data in the respective publications. Type 2 data gaps caused by the complexity of the systems must be 'bridged' by adequate simplifications, hypotheses, or forecasting methods. Approaches for that as well as for type 3 and 4 data deficits will be described in the following chapter. Data gaps of type 5 can only minimised by systematic data collection, but not avoided in principle.

**Table 1:** Categorisation of data gaps in product LCIs ("Time" concerns analysis of past (P), present (PR) or future (F) objects)

| Type | Cause for data gap | Description | Time | Application (Example) |
|---|---|---|---|---|
| 1 | Confidentiality of data | Data is known, but not fully available due to confidentiality | P,Pr,F | Innovative products/ competitive markets (fuel cells), military applications |
| 2 | Complexity of data | Complex processes for which data acquisition is too time consuming or causal relationships are not known | P,Pr,F | Integrated industrial processes (separation of platinum group metals) |
| 3 | Products at an early stage of market development | Processes or technologies not yet fully developed | F | New products (membrane electrode assembly in SOFCs) |
| 4 | Context of product unknown | Background system difficult to forecast | F | Evolving markets (deregulated electricity market) |
| 5 | Lack of knowledge | Due to lack of knowledge processes, components etc. cannot be considered | P,Pr,F | |

Whereas the aspects of infrastructure consideration and background system inclusion may alter the effort for the analysis, they do not pose a fundamental problem. The questions of allocation and determination of 'credit systems' have been addressed in various other publications. Dealing with data gaps, however, requires adequate tools and procedures for meaningful LCAs. In the following, the aspect of forecasting future energy systems is analysed in more detail.

## 2 Forecasting the Production of Future Energy Technologies

When future energy systems are analysed, forecasting is necessary whenever environmentally relevant processes or components have to be assessed based on systems of an immature technology standard. Very often, the forecasting of the use phase, i.e. the performance, emission factors, etc. can be derived either from process modelling, target data from manufacturers information, or emission levels required by environmental legislation. More difficult, however, is the determination of the impacts from the production of future energy technologies which are, at the time of the LCA, very often produced on a lab-scale only.

### 2.1 Procedure

The procedure to assess such future technologies should start from a *preliminary LCI* of the status-quo system, i.e. the system as developed today (compare with Weidema et al. 2002). Then, the data gaps are identified. A relevance analysis shows whether these data gaps have a significant effect on the result of the LCA. Two aspects are important for this step: the process steps to be further investigated must be of environmental relevance, and the parameters of the process steps should exhibit a considerable time dependence.

For those steps (e.g. sintering of a part) or system components (e.g. future catalyst material) with both an environmental relevance and a time dependency a forecast must be carried out. If necessary, the relevant process step or system component should be disaggregated into 'elementary' components. For each of these components, a forecast can now be carried out. It has been proven extremely useful to use independent forecasting methods and check whether the results are consistent. One of the following conditions should then be fulfilled:

- The different results of the independent forecasting methods are consistent, i.e. differ not significantly. Then the data of one of the forecasting methods can be used.
- If the results are not consistent, a sensitivity analysis must be carried out using the results of the different forecasting methods to check whether the results of the LCA are altered.
- If the conclusions of the LCA is influenced by the forecasting method, different scenarios must be created with statements of the type 'If the forecast A is correct, this is the conclusion of the LCA'.

### 2.2 Forecasting methods

A forecasting problem similar to the LCA of future systems arises when costs of future products are analysed. Different cost estimation methods have been developed in management sciences. These methods usually assume that "products with similar characteristics also show similar cost structures" (Schweitzer 1992) (hypothesis of similarity). The forecasting methods as developed in management sciences include

- **Subjective assessment methods** which are based on expert judgements of one or several experts (e.g. opinion survey, brainstorming, experts' consultation). "An advantage of subjective assessment methods is that they can be applied even if not a large database of comparable projects is available." (Schultz 1995) In LCAs, subjective assessment methods are, due to the low ressources required, very common, mainly in form of expert interviews. These methods are often of an intuitive or heuristic nature (e.g. brainstorming). Interviewing several experts in teams or delphi surveys can only be carried out in larger projects (see Contadini et al. 2002). However, the quality of the resulting estimates is strongly dependend on the way the interview is carried out, on the choice of the experts and the qualification of the interview partners.
- **Adaption methods** use "empiric knowledge of completed projects without a formula linking the empiric data." (Schultz 1995) This method is based on a database of comparable projects or processes which are applied for forecasting the relevant components. For that purpose, the analysed process has to be disaggregated into seperate processes for which information is available in the database. Then, a surrogate process has to be searched, i.e. a process from which the data to be forecasted can be

transfered, and the differences to the analysed process have to be identified and considered adequately. Finally, the parameters are transfered and adapted to the LCA. Surrogate processes can be, for instance, processes with similar materials or processing parameters.

In the most simple form, the data from the surrogate process can be transfered without further adaption. This can, for instance, take place in form of coefficients. These coefficients are obtained by dividing a quantity by an adequate parameter to which the quantity shall be related to. The resulting coefficient can then be transfered. The most common example in cost estimation methods is the so-called kilogram/cost method, which assumes that the share of material costs to total production costs is similar for comparable products. To use adaption methods, a large database may be required. The quality of the assessment, however, is often very high. The main advantage of adaption methods is the easy applicability once a database is available. For the quality of the forecast, however, it is essential that the causal relations for both surrogate and analysed process are similar, e.g. a thermal treatment of a material at similar temperatures, in similar quantities, furnaces and furnace loadings.

- Not only data from comparable processes or components can be transferred, but also generalised coefficients derived from other data sources, such as statistics. Based on cost extrapolation, for instance, **input output (I/O) coefficients** can be applied using average energy requirements, emissions, etc. per monetary unit as compiled in national statistics for various production sectors (see Suh and Huppes 2002).
- A common forecasting method is the **regression analysis** starting from a function which correlates one dependent and one or more independent variables using coefficients which are minimised, for instance, using least-square methods (Martino 1973). To use the regression analysis, either the cause-effect relationship must be known (for instance an exponential function for a growth process) or, at least, an empirically proven concept must be used (for instance an S curve for saturated processes or a learning curve correlating the cumulated production to the cost reduction achieved). For a regression analysis, sufficient data from the past must be available. Also, no discontinuities should occur in future developments caused, for instance, by unexpected events or physical constraints. The forecast is then applied by **extrapolating** the regression function to future times. The regression analysis is a very simple tool. The effort of application lies not in the actual forecasting process, but in the collection of data for past developments.
- If no empirical data is available, **modelling the system** can be a powerful alternative. Modelling can be applied on different kinds of product systems, e.g. economic systems, in which the market, the product system and its interactions with exogene variables are analysed, or physical systems based on natural laws.

### 2.3 Criteria for choice of methods

The choice of the best forecasting procedures depends strongly on different factors (**Table 2**). The available data restricts the applicability of certain forecasting methods. The time horizon also influences the selection of the best method. For instance, methods based on extrapolation such as the regression analysis are better suited for short term forecasts, whereas modelling or adaption methods can also characterise long term developments. Further criteria for selecting optimal forecasting methods include flexibility and applicability to different product systems or production processes, required user qualification and reliability. Last but not least, the (financial) volume of the LCA projects can make more extensive methods such as expert panels or model calculations unfeasible. In praxis, a combination of forecasting methods may be appropriate.

**Table 2:** Criteria for selecting forecasting methods in LCA (adapted from Schultz 1995)

| Criteria / Method | | Subjective | Adaption | I/O coeff. | Regression | Modelling | Scenario |
|---|---|---|---|---|---|---|---|
| Time horizon | | SML | SM | SM | SM | SML | SML |
| Required ressources | Required information | + | –/o | + | –/+ ᶿ | o | – |
| | Required user qualification | – | o | + | + | – | – |
| | Speed of usage | +/– * | + | + | o | – | – |
| Quality of results | Reliability | – | –/o | + | + | + | irr |
| | Information content | + | +/o | o | +/o | + | + |
| | Systematic errors? | o/+ | o | – | + | + | + |
| Flexibility | Spectrum of applicability | + | + | + | o | + | + |
| | Adaptability towards changes | +/o | + | + | o | o | o |

S short term; M medium term; L long term

+ advantage of the method • o neutral • – disadvantage of the method • irr: not relevant

* + for single expert interviews, – for Delphi method

ᶿ + if regression equation is available in literature, – if regression equation needs to be researched

### 3 Example: Manufacturing A Fuel Cell Stack

The manufacturing of a Solid Oxide Fuel Cell Stack (SOFC) shall be used as an example for the procedure of a prospective LCI. The manufacturing process (**Fig. 1**) consists of manufacturing the thin electrolyte, screen printing the electrodes and sintering the membrane electrode assembly (MEA). The flow field (bipolar) plates which feed the fuel and the air and collect the electrical current are, in this planar Siemens design, manufactured from chromium alloys which are then isostatically pressed. The channel structure for the gas channels are electrochemically etched. A protection layer and a contact layer are then deposited onto the chromium. In addition, a frame is produced and thermally treated at elevated temperatures. Finally, the layers are assembled, sealed and sintered.

The first streamlined assessment reveals the electricity consumption for sintering the MEAs and the chromium for the flow-field plates as ecologically dominant. The electricity consumption for sintering and drying of 16 $MWh_{el}$ for the stack (see Fig. 1) corresponding to a thermal energy of 15 $MWh_{th}$ is due to the laboratory nature of the sintering furnace and will now be investigated using different forecasting methods.

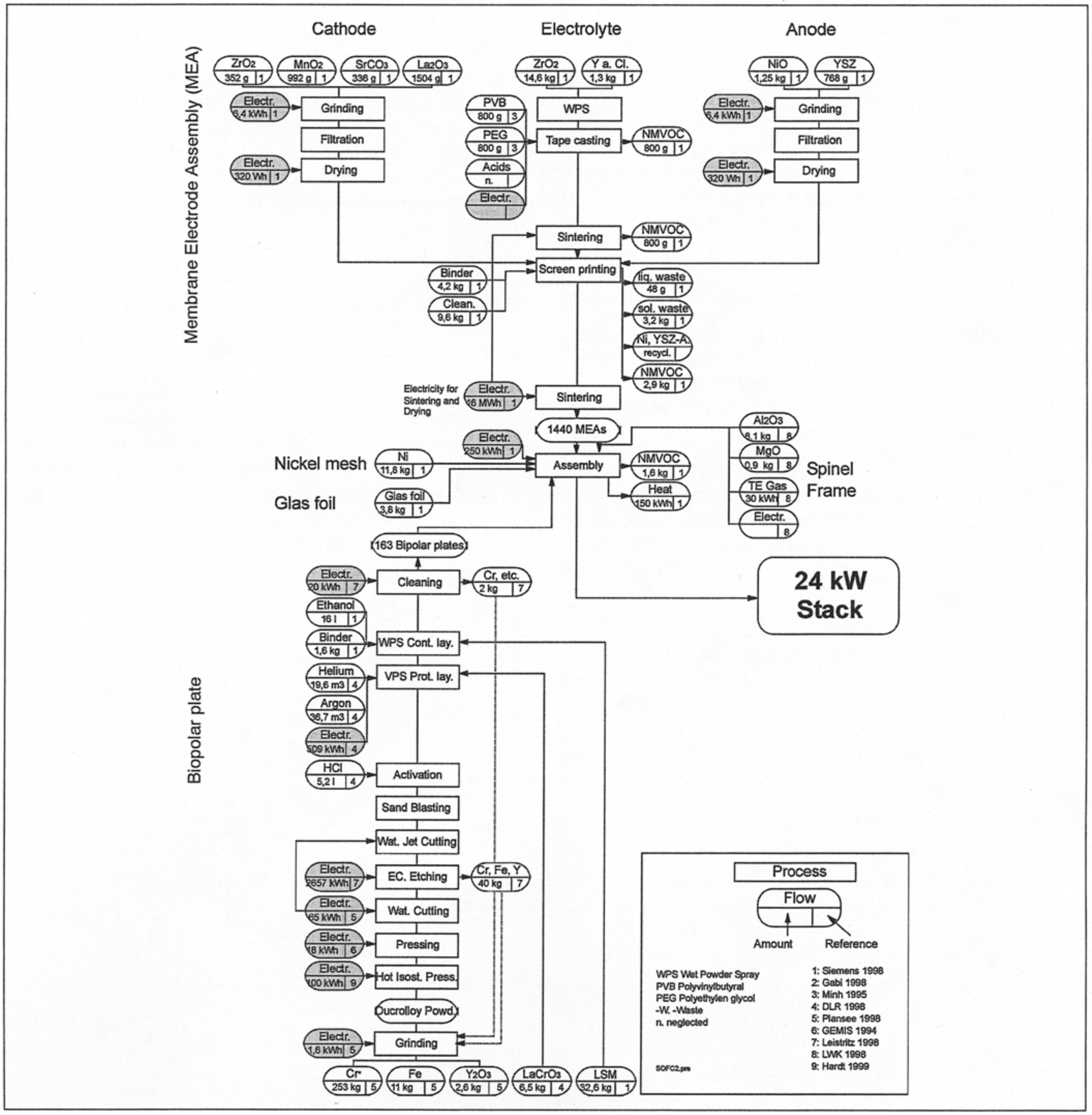


**Fig. 1:** Production process of a planar 24 kW Solid Oxide Fuel Cell (SOFC) stack

(1) Subjective Methods. According to a furnace manufacturer (single expert interview), chamber furnaces as used in the SOFC manufacturing process require 65 % more energy than an industrial furnace for series production (Riedhammer 1998). Thus, a large-scale manufacturing process would require 9 $MWh_{th}$ only. In addition, the chamber furnace used is also laboratory scale, only, so that additional reductions are to be expected.

(2) Adaption method. The surrogate process for sintering the MEA is the production of $Al_2O_3$ ceramics which is carried out under comparable temperatures and sintering conditions. The energy consumption for their production is 50 $kWh_{th}/kg$ (Ruska 1998). Adapting the detailed data (sintering time, calcination of precursor material) to the SOFC process yields 60 $kWh_{th}/kg$ corresponding to 1.44 $MWh_{th}$/stack.

(3) Modelling of the furnace. Modelling the energy balance of the furnace (energy consumption for heating the goods and the furnace materials, radiation, convection and conduction losses) using typical data for industrial furnaces from (IKARUS 1994) yields an energy consumption of 8.8 $MWh_{th}$ and 1.28 $MWh_{el}$ when a distance of 2 cm between the ceramics is assumed (Romero and Wright 1996). The crucial parameter is the volume specific throughput of the furnace.

(4) I/O coefficients. Using the manufacturers cost estimation of 3 €/MEA and typical energy consumption data for German ceramic goods from the national statistics yields a primary energy demand of 13.9 $MWh_{th}$ and 2.24 $MWh_{el}$, if other materials and energy input for further process steps are taken into account.

**Fig. 2** compares the results of the various forecasting methods. Accept for the I/O coefficients, reduction factors of at least two for the thermal energy demand are achieved. However, the results of the various methods differ. Hence, modelling the furnace using empirical data for commercially available furnaces is chosen as the default value for the LCA, the results of which are comparable to the subjective estimations of furnace suppliers, whereas the adaption method is applied in a sensitivity analysis to characterise the minimum energy consumption to be expected.

## 4 Conclusions

The selection of a suitable forecasting method depends on different factors such as required ressources, quality of the results and flexibility. In particular, the time horizon of the investigation determines which forecasting tool may be applied.

However, the example production of an SOFC stack shows that the calculated environmental impacts of a production process may differ significantly depending on the forecasting method. Thus, after identifying the environmental hot spots of the system under investigation, e.g. the production process, the relevant process steps shall principally be investigated using at least two independent forecasting tools. If the results do not converge a sensitivity analysis must be carried out to ensure that the LCA conclusions are nevertheless robust.

## 5 Outlook

Whereas this paper focussed on the methodological issues associated with assessing future energy systems, Part 2 of this publication will present results of the LCA study of fuel cells in mobile and stationary applications. At various steps of these LCAs, forecasting is required. **Table 3** gives some examples of such parameters and also indicates which forecasting methods were selected for the analysis.

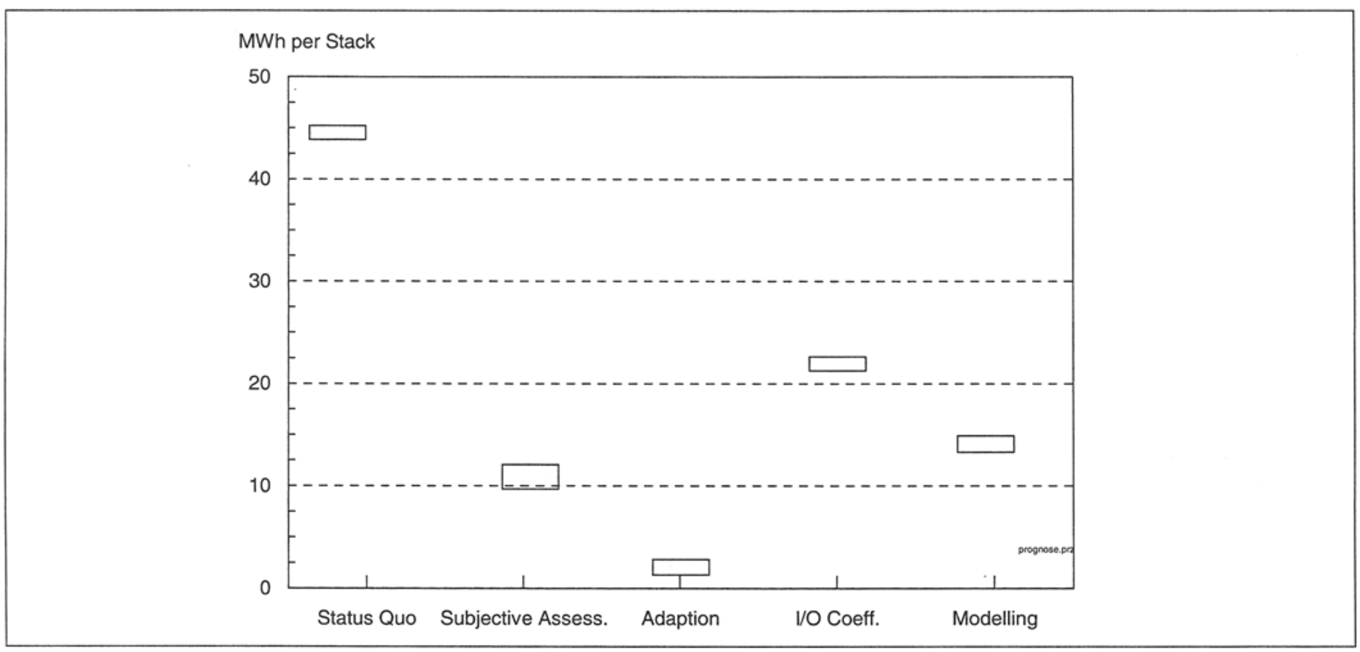


**Fig. 2:** Primary energy consumption for sintering and drying one SOFC stack: results of the various forecasting methods

**Table 3:** Further examples of parameters requiring forecasting and the forecasting methods selected

| Parameter | Forecasting method | Cross check forecasting method |
|---|---|---|
| Platinum content in PEFC | Trend extrapolation | Experts' consultation; included in sensitivity analysis |
| Energy consumption of future $H_2$ liquefication | Regression analysis using experimental data for large-scale systems | Maximum thermodynamic efficiency to determine optimal performance |
| Methanol distribution paths | Different distribution scenarios | |
| Electrical efficiency of future power plants | Transfer of BAT data | Experts' consultation; included in sensitivity analysis |
| Natural gas import mix | Opinion survey | |
| Future ICE fuel consumption | Modelling of lab-scale combustion engines | Transfer of BAT data |
| Fuel cell fuel consumption | Power train modelling | Experts' consultation (target data); included in sensitivity analysis |
| Balance of plant of SOFC and PEFC | Transfer of PAFC data | |

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